Towards Coupling Rare Earth Ions to a Y_2SiO_5 Nanophotonic Resonator

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Abstract: An yttrium orthosilicate nanophotonic resonator is fabricated with resonances near the $^4I_{9/2}$-$^4F_{3/2}$ hyperfine transition of Neodymium ions. Measured absorption by Neodymium embedded in a nanobeam indicates promising prospect for coupling ions to our nano-resonator.

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Very long spin and optical coherence times of 4f-4f transitions in rare earth ions (REI) [1] make them promising candidates for implementing solid-state quantum information storage and scalable quantum computation. When embedded in nano-structures, the effective shielding of 4f electrons in REI hints at a reduced spectral diffusion and blinking that are common in quantum emitters based on quantum dots [2] and nitrogen-vacancy (NV) centers [3], therefore making REI better suited for nano-scale quantum photonic applications. The first important step towards REI based quantum photonic platform is to couple REIs efficiently to high quality micro/nano scale optical resonators with a small mode volume. This cavity-assisted coupling enhances the coherent interaction between REIs and photons, meanwhile allowing the emission from ions to be collected with high efficiency. Here, we demonstrate a photonic crystal nano-resonator fabricated in a Neodymium (Nd) doped Yttrium orthosilicate Y_2SiO_5 crystal, achieving quality factor Q ~3100 with a small mode volume $V = 1.65(\lambda / n_{YSO})^3$ near the 883 nm $^4I_{9/2}$-$^4F_{3/2}$ hyperfine transition of Nd^{3+}. We measured the resonant absorption of Nd^{3+} ions embedded in a FIB fabricated nanobeam without the cavity. The result was on par with a unprocessed bulk Nd^{3+}:Y_2SiO_5 sample, suggesting that the embedded ions are inert to our fabrication process, which bodes well for quantum nanophotonic applications requiring efficient coupling between REI and nano-resonators.

The schematic of a Nd^{3+}:Y_2SiO_5 nano-resonator is illustrated in Fig. 1. A 1D photonic crystal cavity is formed on top of a triangular nanobeam waveguide. The cavity is formed by 40 equally spaced groves except for in the center of the beam where we introduce a defect by perturbing the lattice constant a with a parabolic profile similar to the design in [4]. The depth of the groves is 60% of the beam height, while the beam cross section is an equal-lateral triangle with 60° internal angles. Simulation of the structure with dimensions in Fig. 1 reveals a resonance mode at 883 nm corresponding to the $^4I_{9/2}$-$^4F_{3/2}$ transitions of Nd^{3+} ions. The cross sectional and side views of this mode field profile are also shown in Fig. 1. The simulated quality factor Q for this mode is ~5×10^5 with a mode volume $V = 1.65(\lambda / n_{YSO})^3$.

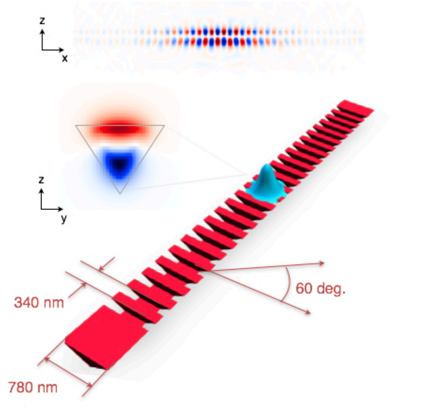

Fig. 1 Schematic of a Y_2SiO_5 nano-resonator. The field profiles correspond to a resonance mode at 883 nm.

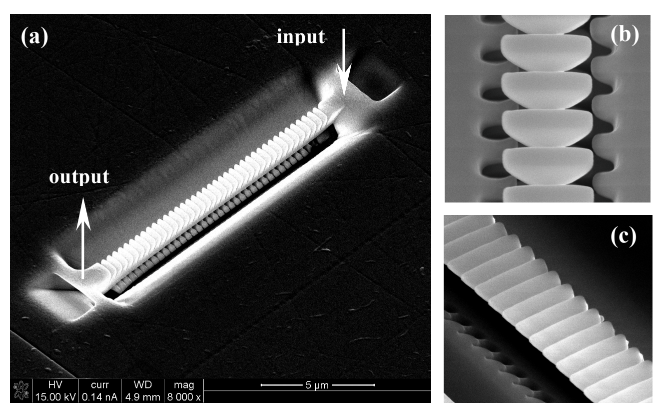

Fig. 2 Scanning electron microscope images of a FIB fabricated Y_2SiO_5 nano-resonator. (b, c) Close-up views of the milled groves on a triangular nanobeam.

The triangular nanobeam resonator was fabricated using focused ion beam (FIB). Fig. 2 shows the scanning electron microscope images of a FIB fabricated device. Coupling in and out of the cavity was realized by two 45° angled reflectors on Y_2SiO_5 at both ends of the nanobeam. These reflectors allow vertical excitation and efficient collection of the cavity emission using our custom built confocal microscope setup.

We first measured the resonant absorption through a 15-μm 0.03% Nd^{3+}:Y_2SiO_5 nanobeam without the cavity at a temperature of 77 K. A confocal beam from a 50-nm bandwidth superluminescent diode (SLD) centered at 860 nm was vertically coupled into the waveguide, and the transmitted light was collected and sent to a high-resolution spectrometer. Fig. 3 (a) plots the spectrum of the transmitted light, in which two transitions of Nd^{3+} at 883.1 nm and 884.0 nm are clearly seen. The measured resonant absorptions are 0.12 and 0.1 OD for the two transitions, respectively, which compare favorably with the 3.7 OD absorption of a 1-mm-long 0.03% Nd^{3+}:Y_2SiO_5 bulk sample that was not micromachined by FIB. This result suggests that the hyperfine transitions in Nd^{3+} were not significantly affected by the FIB process. Hence it is promising to realize coupling to Nd^{3+} ions with our device.

Next we measure the cavity resonances by excitation from a supercontinuum white light source. The upper part of Fig. 3 (b) shows an infrared image of the excited resonator. A faint spot at the center of the nanobeam indicates the cavity mode confinement. The room temperature spectrum of the transmitted light through the Y_2SiO_5 nano-resonator is plotted in Fig. 3 (b) for both TE and TM polarizations. Several resonant peaks in the photonic bandgap (~700 - 1000 nm, band edges not shown in the plot) were identified for both TE and TM signals. The measured spectrum shows good agreement with the simulation, with the resonance peaks shifted to longer wavelengths from the theoretical values by 15-20 nm. We attribute these ~2% offsets to the fabrication tolerance of the current FIB process. Consequently, we identify the spectral peaks with their respective mode profiles, as labeled in Fig. 3 (b). Our designed resonance mode occurred at 898.2 nm. The measured quality factor is ~3100 as shown in the inset. Cooling the device down to 77 K shifted the resonance wavelength to 897.3 nm without degrading the Q. Currently we are optimizing the design for better matching with the Nd^{3+} transitions.

The goal, after we successfully tune the resonance to the target transition lines, is to demonstrate an enhanced coupling via the Purcell effect of cavity photons to the Nd^{3+} ions that are indeterministically embedded in the Y_2SiO_5 cavity. The Q/V ratio of ~1800 of our device yields a theoretical Purcell factor of 138, which could be measured by a strongly enhanced absorptions at 883 or 884 nm than that in Fig. 3, or by a reduced photon lifetime of spontaneous emissions from the Nd^{3+} ions. Finally, we also note that our current device performance is sufficient for demonstrating detection of a single ion [5].

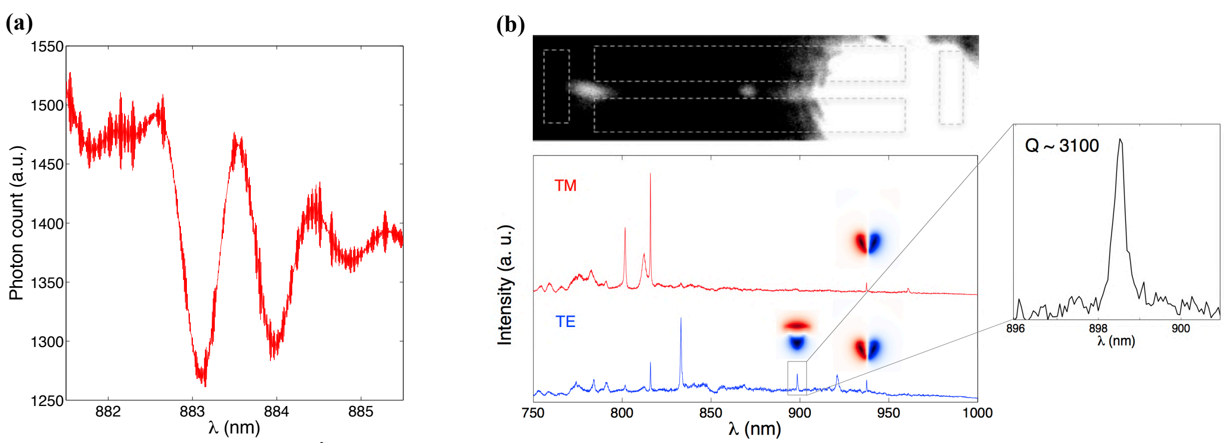

Fig. 3 (a) Resonant absorption of Nd^{3+} embedded in a 15-μm-long FIB fabricated triangular waveguide at 77 k, showing two transitions at 883.1 nm and 884.0 nm. (b) Measured room temperature transmission spectrum of an Y_2SiO_5 nano-resonator for TE and TM polarizations. The top infrared image shows the excited cavity modes near the center of the nanobeam. The resonance mode at 898.2 nm has Q~3100, as shown in the inset.

References

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